An overview of the underestimated magnetic loop HF antenna

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It seems one of the best kept secrets in the amateur radio community is how well a small diminutive magnetic loop antenna can really perform in practice compared with large traditional HF antennas. The objective of this article is to disseminate some practical information about successful homebrew loop construction and to detail the loop's key distinguishing characteristics and unique features. A magnetic loop antenna can very conveniently be accommodated on a table top, hidden in an attic/roof loft, an outdoor porch, patio balcony of a high-rise apartment, or any other space constrained site.

A small but efficacious HF antenna for restricted space sites is the highly sought after Holy Grail of many an amateur radio enthusiast. This quest and interest is particularly strong from amateurs having to face the prospect of giving up their much loved hobby as they move from suburban residential lots into smaller restricted space retirement villages and other communities that have strict rules against erecting elevated antenna structures.

In spite of these imposed restrictions, amateurs do have a practical and viable alternative means to actively continue the hobby using a covert in-door or portable outdoor and sympathetically placed small magnetic loop.

This paper discusses how such diminutive antennas can provide an entirely workable compromise that enable keen amateurs to keep operating their HF station without any need for their previous tall towers and favourite beam antennas or unwieldy G5RV or long wire. The practical difference in station signal strength at worst will be only an S-point or two.

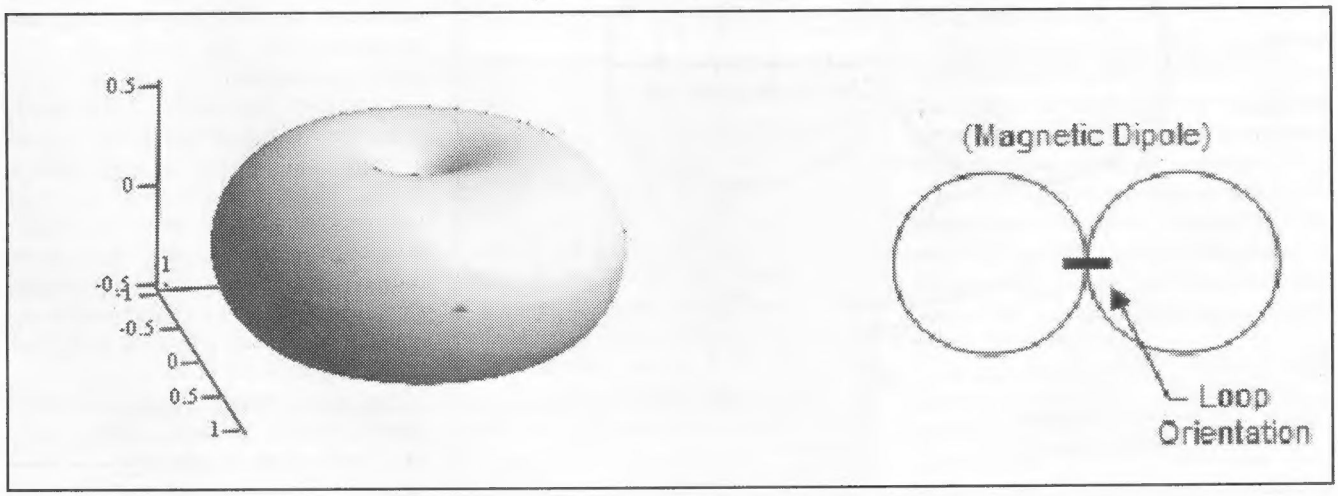
Anyone making a cursory investigation into the subject of magnetic loop antennas using the Google internet search engine will readily find an overwhelming and perplexing abundance of material. This article will assist readers in making sense of the wide diversity of often times conflicting information with a view to facilitate the assimilation of the important essence of practical knowledge required to make an electrically-small loop work to its full potential and yield good on-air performance.

A few facts

A properly designed and constructed small loop of nominal one metre diameter will outperform any antenna type except a beam on the 10 m/15 m/20 m bands, and will be within an S-point (6 dB) of an optimised mono-band beam that is mounted at an appropriate height above ground.

Magnetic loops really come into their own on the higher HF bands from, say, 40 m through to 10 m; oftentimes with absolutely stunning performance rivalling the best conventional antennas. Easily field deployable and fixed site tuned loops have been the routine antenna of choice for many years in professional defence, military, diplomatic, and shipboard HF communication links where robust and reliable general coverage radio communication is deemed mandatory.

So where is the catch; if the small loop is such a good antenna why doesn't everyone have one and dispense with their tall towers? The laws of nature and electromagnetics cannot be violated and



Magnetic loop radiaton patternn diagram

the only price one pays for operating with an electrically-small antenna is narrow bandwidth. Narrow instantaneous bandwidth rather than poor efficiency is the fundamental limiting factor trade-off with small loops.

Any small antenna will be narrow band and require tuning to the chosen operating frequency within a given band. Users of magnetic loops must be content with bandwidths of say 10 or 20 kHz at 7 MHz or a little more than 0.2%. They are content as long as the antenna can be easily tuned to cover the frequencies that they wish to use. For a remotely sited or rooftop mounted antenna this requires just a modicum of that ingenuity and improvisation for which radio amateurs are renowned.

A small loop antenna for transmitting is defined as having a circumference of more than one-eighth wavelength but somewhat less than one-third wavelength which results in an approximately uniform current distribution throughout the loop and the structure behaves as an inductance.

The doughnut shaped radiation pattern is in the plane of the loop with nulls at right angles to the plane of the loop. The loop self-inductance can be resonated with a capacitance to form a high-Q parallel tuned circuit. The attainment of a high-Q tells us that the loop antenna is not lossy and inefficient.

When power is applied to the loop at its resonant frequency all of that power will be radiated except that portion absorbed in the lumped I^2R conductor and capacitor losses manifesting as wasteful heat. With proper design these series equivalent circuit losses can be made negligible or at least sufficiently small compared to the loop's radiation resistance that resultantly high intrinsic radiation efficiency and good antenna performance can be achieved.

Current through the loop's radiation resistance results in RF power being converted to electromagnetic radiation. However, since the small loop's radiation resistance is very small compared to that of a full sized resonant ½λ dipole, getting this favourable ratio of loss to radiation resistance is the only 'tricky' and challenging part of practical loop design and homebrew construction.

Through utilizing a split-stator or a butterfly style air variable capacitor construction or a vacuum variable capacitor, low loss can be achieved in the tuning capacitor. Conductor loss can then be controlled by optimal choice of the diameter of copper tubing used to form the loop element and paying very careful attention to low ohmic interconnections to the capacitor such as welded or silver soldered joints, etc. With 100 Watts of TX drive power there are many tens of Amperes of RF circulating current and Volt-Amps-Reactive (VAR) energy flowing in the loop conductor and tuning capacitor.

Capacitor losses are further minimised by welding the rotor and stator plates to the stacked spacers to eliminate any residual cumulative contact resistance. When connected across the loop terminals the butterfly construction technique inherently eliminates any lossy rotating contacts in the RF current path.

The configuration permits one to use the rotor to perform the variable coupling between the two split stator sections and thus circumvent the need for any lossy wiper contacts to carry the substantial RF current. Since the fixed stator plate sections are effectively in series, one also doubles the RF breakdown voltage rating of the composite capacitor.

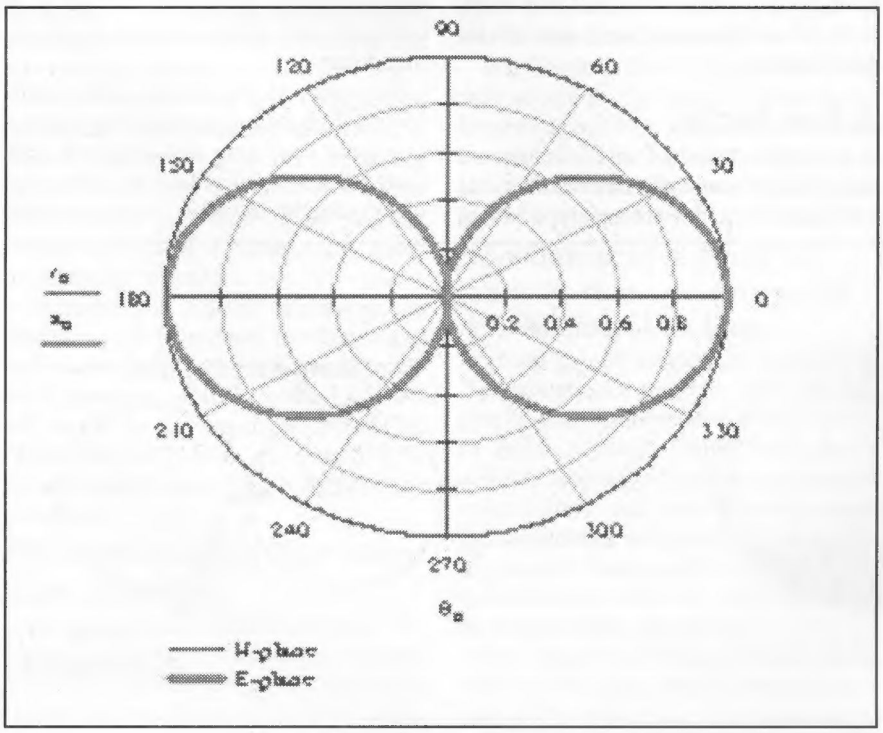
In view of the fact the loop antenna is a high-Q resonant circuit, many kilovolts of RF voltage can be present across the tuning capacitor and appropriate safety precautions must be taken. Loop antennas capable of handling a full 400 Watts PEP are readily achievable when appropriate construction and tuning components are selected.

Although loop antennas have deceptively simple appearance, they are complex structures with radiation patterns and polarisation characteristics dependent on whether they are fed in a balanced or unbalanced fashion. The method of feeding and matching the loop resonator, ground plane configuration, as well as the geometric form factor and physical proportions of the loop element itself are all fertile ground for experimentation.

Various matching methods include series capacitor, transformer coupled subsidiary shielded-Faraday loop, and gamma-match, etc; each with their respective merits.

Small loop antennas have at least two simultaneously excited radiation modes: a magnetic and an electric folded dipole mode. When the ratio proportions of loop mode and dipole mode radiation are juggled to achieve equal strengths some radiation pattern asymmetry results and a useful degree of uni-directionality can be achieved with a typical front to back ratio of about 6 dB or so.

The small loop with its doughnut shaped pattern exhibits a typical gain of 1.5 dBi over average ground and a gain of 5 dBi when deployed with either



Magnetic loop field amplitude diagram

short radials (the length of each radial need only be twice the loop diameter) or mounted over a conductive ground plane surface. By comparison a large ½λ horizontal dipole mounted ¼λ above average ground has a gain of 5.12 dBi and a ¼λ vertical with 120 radials each ¼λ long has a gain of 2 dBi over average ground. The front to side ratio of a loop is typically 20 to 25 dB.

However the small loop has one very significant advantage over any other antenna due to its unique radiation pattern. If the vertically oriented loop's figure-8 doughnut pattern radiation lobe is visualised standing on the ground the maximum gain occurs at both low and high angles, radiating equally well at all elevation angles in the plane of the loop, that is, radiation occurs at all vertical angles from the horizon to the zenith.

Because the loop radiates at both low and high angles, a single loop can replace both a horizontal dipole and a vertical. This is particularly beneficial on 160, 80 and 40 m where the loop will provide outstanding local/regional coverage and easily match and often outperform a tall ¼λ vertical for long haul DX contacts, that is, an exceptionally good general purpose antenna.

Energy radiated by the small loop is vertically polarised on the horizon and horizontally polarised overhead at the zenith. It will be quickly realised that a loop has the distinctive property of providing radiation for transmission and response for reception over both long distances and over short to medium distances. This is achieved by virtue of low angle vertically polarised propagation in the former case and by means of horizontally polarised oblique incidence propagation in the latter case. In contrast, a vertical monopole is useful only for low angle vertically polarised propagation since it exhibits a null overhead and poor response and radiation at angles in excess of about 45 degrees. Such antennas are of course very useful for long distance communication by means of low angle sky wave skip propagation, or for short range communication via the ground wave propagation mode.

In further contrast, a horizontal ½λ dipole (or beam arrays comprising dipole elements) at a height above ground of just a fraction of a wavelength (as opposed to idealised free space or mounted very high) exhibits maximum polar response directly overhead (good for NVIS) with almost zero radiation down near the horizon. Such popular 'cloud warmer' antennas in residential situations as the surreptitiously hung ubiquitous G5RV, end-feds, dipoles, inverted-V, etc. are thus most useful for short to medium range communication in that portion of the HF radio spectrum where oblique incidence propagation is possible.

Importantly it should be noted when comparing small loops with conventional antennas that a 20 m Yagi beam, for example, must ideally be deployed at a height above ground of at least one wavelength (20 m) in order to work well and achieve a low take-off angle tending towards the horizon for realising optimal no compromise long-haul DX operation.

Unfortunately such a tower height is impractical in most residential zoning rule situations imposed by municipal councils and town planners. If the Yagi beam is deployed at a lower 10 m height then a diminutive loop will nearly always outperform the beam antenna.

This writer never fails to be amused by folks who acquire a potentially high performance Yagi HF beam and sacrilegiously deploy it in suboptimal installations in respect of height above ground or proximity to a metal roof. The problem worsens on the lower bands below 20 m where the resultant lobe pattern direction is not at all very conducive to facilitating good DX communication.

In comparison to a vertically mounted/oriented loop, the bottom of the loop does not need to be more than a loop diameter above ground making it very easy to site in a restricted space location. There is no significant improvement in performance when a small loop is raised to great heights; all that matters is the loop is substantially clear of objects in the desired direction of radiation! Mounting on an elevated roof ground-plane yields excellent results.

A good HF antenna for long haul DX requires launching the majority of the TX power at a low angle of radiation; things a good, efficient and properly installed vertical, a properly sited small magnetic loop, and a big multi-element beam atop a very tall tower do very well.

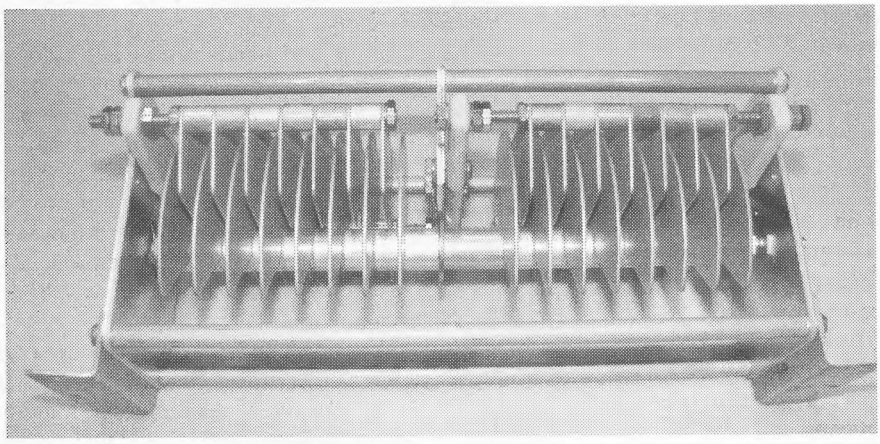
Receiving properties

In a typical high noise urban environment a loop will nearly always hear more than a big beam on the HF bands. The small magnetic loop antenna (a balanced one) responds predominately to the magnetic component of the incident EM wave, while being nearly insensitive to the electric field component; which is the basic reason why loops are so impressively quiet on receive; often times dramatically so.

They will pull in the weak signals out of the ambient noise and you will very likely receive stations that you would never hear when switching across to a vertical, dipole or beam antenna.

In a propagating radio wave the magnitude of the electric vector is 120Ω or 26 dB greater than the magnitude of the magnetic vector, the difference being due to the intrinsic impedance of free space (377 Ohms).

On the other hand the induction fields associated with man-made noise have electric E-field components many times greater than a normal radiation field (radio wave). While a dipole or vertical



Split stator butterfly capacitor

antenna is sensitive to both the electric and magnetic components of a wave, the small loop is responsive only to the magnetic H-field component and it will be substantially 'blind' and offer a high degree of rejection to pickup of undesired man made noise and atmospheric disturbances.

Hence the widely used term 'magnetic loop' antenna to signify this field discrimination to the components of the incoming incident EM wave. Antenna theory treats the loop as the electrical conjugate of the dipole, that is, the loop is a 'magnetic dipole' while an ordinary dipole is an 'electric dipole'.

Significantly, a small loop antenna will typically produce a signal-to-noise ratio (SNR) that is some 10 to 20 dB greater than a horizontal dipole in a noisy urban environment and an even greater improvement in SNR when compared to a vertical antenna as a result of the man-made noise comprising a strong electric field component and being largely vertically polarised.

The most important criterion for reception is the signal to noise ratio and not antenna gain or efficiency. In the HF bands, particularly at the low-mid frequency portion, external man-made and galactic/atmospheric noise is dominant.

The magnetic loop antenna has one other important practical advantage in receive mode. The aforementioned high-Q resonator imparts a very narrow band frequency selective bandpass filter ahead of the RX front-end stages.

Such an incidental preselector comprising the antenna itself imparts greatly improved receiver performance on the congested lower HF bands with high power broadcast stations and particularly when lightning strikes and atmospheric electrical discharges are present in the regional area. Unwanted overload causing and adjacent-channel QRM interference signals are rejected or heavily attenuated.

As well as eliminating strong-signal overload and intermodulation effects, the filtering dramatically reduces the amount of lightning induced broadband impulse energy fed to the RX front-end and weak signals can still be heard when reception under such adverse conditions was previously impossible.

It is these collective characteristics of small loop antennas that enable them to often very significantly outperform their large dipole, Yagi or Quad beam counterparts during direct A/B comparative testing. Conversely in TX mode the antenna's inherent filter action selectivity causes any transmitter harmonics to be greatly attenuated and not radiated. This can help with eliminating some forms of TVI.

Construction and siting issues

Without a good quality low-loss split stator or butterfly or vacuum variable capacitor of adequate RF voltage and current rating, it is quite futile building a magnetic loop antenna and expecting it to yield the impressive results of which it is potentially capable.

The minimisation of all sources of loss is particularly important in TX mode. By virtue of the shorter rotor, the butterfly style capacitor has slightly lower rotor loss than the split-stator construction style. The tuning capacitor is undoubtedly the single most critical component in a successful homebrew loop project.

Although more expensive and harder to find, vacuum variable capacitors have a large capacitance range in respect of their min/max ratio and allow a loop to be tuned over a considerably wider frequency range than that achievable with an air variable capacitor. Vacuum capacitors also have lower intrinsic losses than most air variables.

Good quality Jennings vacuum variable capacitors and a multitude of Russian made equivalents can be readily found on the surplus radio parts markets and eBay, as can their associated silver-plated mounting and clamp hardware to ensure a low contact resistance connection to the loop antenna conductor.

Other creative means can also be used to fashion a high VAR rated low-loss capacitor such as trombone, piston, or interdigitated meshing plate configurations. Air is always the preferred dielectric as most other materials have high loss tangents and dissipation factors.

Whether a vacuum or air variable or homebrew capacitor is chosen, their mechanical shafts can be readily interfaced to a reduction gearbox and motor drive to facilitate easy remote tuning of a roof top or covert loft mounted loop. The antenna tuning can be manual or automatic based on VSWR sensing and a self-tuning servo system to control the drive motor.

Failure to pay very careful, strict attention to construction details in relation to eliminating all sources of stray losses and making bad siting choices such as close proximity to ferrous materials are the two main reasons why small magnetic loop antennas sometimes fail to live up to their performance potential; instead behaving as a proverbial 'wet noodle' with associated poor signal reports. Conversely a well built/sited loop is an absolute delight.

Transmitting loop antennas intended for optimal coverage of the most popular portion of the HF spectrum from 3.5 MHz to 30 MHz are best segregated into at least two distinct loop sizes. A nominal 0.9 m diameter loop for covering all the upper HF bands from 20 m through to

Vacuum capacitors

10 m (and perhaps also tunable down to 30 m depending on capacitor min/max ratio), and a 2 m diameter loop for covering the lower bands 80 m through to 30 m. For best operation down at 160 m and improved 80 m performance increased loop diameters of 3.4 m to 4 m should be considered.

Top band operation at 1.8 MHz is always the hardest challenge for any antenna type, small loops (typical dimensions of 0.02λ) included, but their on-air performance can nevertheless be authoritative with a commanding signal presence.

There are however, no 'free lunches' (and few cheap ones) when shrinking the size of antennas as the free space wavelength has not yet been miniaturized by nature redefining the laws of physics! Consequently antennas of such diminutive size must always be placed into proper perspective when compared with the performance attainable from a full-sized λ/2 horizontal dipole for 160 m.

Most amateurs do not have sufficient residential block size and/or mast height in a fraction of wavelength to accommodate a 160 m dipole that works properly with a decent radiation efficiency and ability to put its radiated power in a useful direction. Similarly, reasonably efficient and efficacious verticals for 160 m operation unfortunately exceed, by a great margin, the height permitted by local council and residential building code regulations.

The performance on the 160/80 m bands will be highly dependent on what antenna you use as a reference comparison, for example, a centre-loaded mobile whip or full size dipole/monopole, or whatever and what path is used, NVIS, ground wave, sky wave, etc.

The loop conductor diameter is determined by the desired loss resistance due to skin-effect, and choices can range from modest 6 mm copper tubing to large bore 100 mm copper or aluminium tube. Commonly used conductor diameters used to construct a magnetic loop are 20 mm and 32 mm soft copper tube.

Note that the radiation efficiency is not related to the loop size. Loop antenna efficiency is determined by the conductor tube diameter and its conductivity. This conceptual notion is counterintuitive for many folks.

A small loop will also be efficient and radiate power very effectively on 80 m and 160 m but the resultant L/C ratio and stored energy will often be such that the loop's Q factor will be so high as to yield an impractically small instantaneous bandwidth that is not useful for SSB communication purposes.

Achievable bandwidth is roughly proportional to loop size/diameter and Q is inversely proportional to the loop diameter. Depending on its construction, a small loop of nominal one metre diameter can exhibit an intrinsic radiation efficiency of 90% over the 1.8 to 30 MHz frequency range.

Copper tubing is the preferred material to fabricate the loop as it has a higher conductivity than aluminium. Larger size semi-rigid Heliax coax such as LDF550 will conveniently make excellent loop construction material for the smaller diameter 20 m to 10 m HF band loops when run at the 100 Watt power level.

In relation to resistance and conductivity, small loop antennas inherently exhibit very low radiation resistances, which compete with the ohmic resistances of the loop conductor and the resistances from connections and

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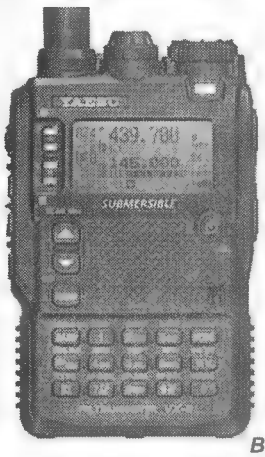
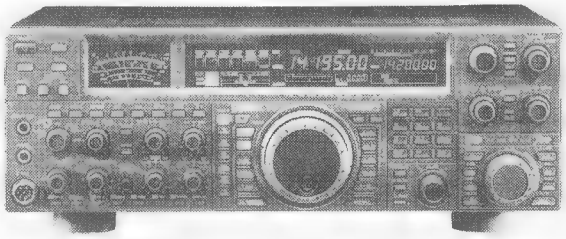
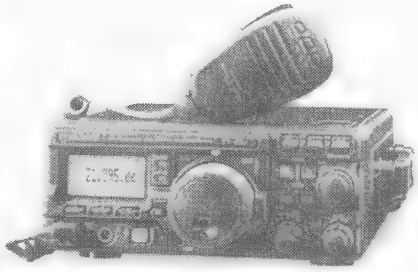




FT-2000/D HF/50 MHz Transceiver

From Handhelds to HF



VX-8R Triple Band Handheld

FT-897D All Mode 1.8-430 MHz Transceiver

welds, including the tuning capacitor connection.

Magnetic loop antennas will typically have a radiation resistance in the order of 100 to 200 milliohms. This means that every additional milliohm caused by a poor contact will cost you one percent efficiency. That is why professional magnetic loop antennas for transmitting purposes will never have mechanical contacts and everything including the capacitor plates should be welded or soldered.

It is common to experience 60 Amperes or more of RF circulating current in the loop and capacitor when fed with several hundred watts of power.

In the practical deployment and siting of a loop antenna there are extrinsic factors of both a beneficial and deleterious kind affecting the radiation and loss resistances when the loop is not strictly deployed in a free space scenario.

When the loop is mounted over a perfectly conducting ground plane reflector or copper radial wire mat, an electrical image is created that effectively doubles the loop area. This in turn beneficially increases the loop's radiation resistance by a substantial factor of four times. Such a situation is easy to facilitate.

Conversely if the loop is placed over average ground (a reasonable reflector) the radiation resistance increases but a reflected loss resistance is also introduced due to transformer effect coupling near-field energy into the lossy ground.

Similarly when ferrous/iron material is too close, the magnetic near-field of the loop will induce by transformer action a voltage across the RF resistance of the material causing a current flow and associated I2R power loss. This situation might arise for example when the loop is mounted on an apartment balcony with nearby iron railing or concrete rebar, or similar; the deleterious influence can be minimised by simply orienting the loop to sit at right angles to the offending iron or steel material.

Another loss contributing component is due to current flowing in the soil via capacitance between the loop and the soil surface. This capacitive coupling effect is again minimised by keeping the loop at least half a loop diameter or more above the ground.

The transformer analogy for the loop antenna is a good one. The HF communication link may be visualised as a reciprocal 'space transformer' with the loop acting as a secondary 'winding' loosely coupled to the distant transmitting antenna. The magnetic field component of the incident electromagnetic wave induces a small RF current to flow in the loop conductor by means of induction that in turn gets magnified by the loop resonator's high Q that is appropriately impedance matched to the coax transmission line.

A freestanding loop is best supported a metre or two in height on a short non-metallic mast section of 100 mm diameter PVC drainpipe and pedestal foot fashioned from plastic plumbing fittings. The loop can also be placed on a rotator drive and turned for best signal strength or it can be oriented in angle to null-out particularly bad QRM.

Care must be taken not to touch the loop when transmitting and to keep a safe distance away from the loop's magnetic near-field to ensure conservative compliance with EMR standards for human exposure to EM fields. A distance equal to or greater than one or two loop diameters away is generally a safe field strength region. RF burns to the skin from touching the loop while transmitting are very unpleasant and take a long time to heal.

Concluding remarks:

The proof of the pudding is always in the eating so experimentally inclined amateurs are encouraged to gain some first hand experience by getting into the shack and constructing some homebrew loops. Such empirical validation of efficacy is always very gratifying, particularly when a VK station can have a solid 5 and 9+ QSO on 20 m with a USA or Canadian station from an elegant looking Lilliputian indoor loop sitting on a table fed with a modest 50 Watts!

What we ultimately seek from any antenna is reliable HF communication at all times when a band is open for DX and, simply put, that means radiating most of the RF that is applied to the antenna in a useable direction and take-off angle.

The underestimated magnetic loop antenna satisfies that basic criteria very well.

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